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[71] 申请人 华为技术有限公司
地址 518057 广东省深圳市科技园科发路华为用服大厦
[72] 发明人 林 东

[74] 专利代理机构 北京德琦知识产权代理有限公司
代理人 张颖玲

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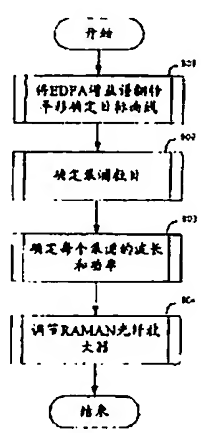
[54] 发明名称 喇曼掺铒光纤放大器的增益谱均衡的方法

[57] 摘要

本发明公开了一种使喇曼掺铒光纤放大器增益谱均衡的方法，应用于含有至少两个以上不同波长泵浦的喇曼光纤放大器，包括以下步骤：a. 将掺铒光纤放大器增益谱线翻转，等比例平移到与喇曼光纤放大器增益谱线的所在位置范围，并设定该平移后的增益谱线为目标曲线；b. 根据目标曲线、精度要求以及成本确定喇曼光纤放大器的泵浦数目；c. 根据目标曲线、精度要求以及步骤 b 得到的泵浦数目确定每个泵浦的波长和功率值；d. 根据步骤 b 和步骤 c 的结果调节喇曼光纤放大器。通过本发明方法能够使喇曼掺铒光纤放大器的增益谱线更加平坦，以减小 GFF 的深度，提高 GFF 的可生产性，从而降低放大器的内部插损、噪声、功率损耗，及其成本。



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1、一种使喇曼掺铒光纤放大器增益谱均衡的方法，应用于含有至少两个以上不同波长泵浦的喇曼光纤放大器，其特征在于包括以下步骤:

a. 将掺铒光纤放大器的增益谱线翻转，等比例平移到喇曼光纤放大器增益谱线所在的位置范围，并设定该平移后的增益谱线为目标曲线;

b. 根据目标曲线、精度要求以及成本确定喇曼光纤放大器的泵浦数目;

c. 根据目标曲线、精度要求以及步骤b得到的泵浦数目确定每个泵浦的波长和功率值;

d. 调节喇曼光纤放大器中的泵浦数目为步骤b所确定的泵浦数目，调节喇曼光纤放大器中每个泵浦的波长和功率为步骤c所确定的波长和功率值.

2、根据权利要求1所述的方法，其特征在于，步骤c中喇曼光纤放大器每个泵浦波长和泵浦功率的确定是通过单纯形算法与共轭方向算法相结合的工程优化方法实现。

3、根据权利要求1所述的方法，其特征在于：步骤b所述的精度要求是将输出增益谱的平坦度控制在固定范围内。

4、根据权利要求2所述的方法，其特征在于所述的单纯形算法与共轭方向算法进一步包括:

c1. 以每个泵浦的波长和功率值分别作为优化变量，构造一个单纯形，采用单纯形算法对其进行优化;

c2. 对步骤c1优化后得到的含有优化变量的顶点采用共轭方向算法进一步优化，直到对优化变量通过仿真算法得到的性能曲线与目标曲线接近到满足精度要求.

5、根据权利要求4所述的方法，其特征在于，步骤c1进一步包括：将至少两倍于优化变量的值作为优化变量数目，构造一个单纯形.

6、根据权利要求4所述的方法，其特征在于，步骤c2中所述性能曲线与目标曲线接近到满足精度要求是所得性能曲线相对目标曲线的误差平方和小到

精度允许的范围。

喇曼掺铒光纤放大器的增益谱均衡的方法

技术领域

本发明涉及一种喇曼掺铒光纤放大器技术，特别是使喇曼掺铒光纤放大器的增益谱均衡的方法。

背景技术

现有的光网络系统，均已采用光放大器作为中继单元，对经光纤传输后衰减的信号进行放大，使信号向下一级传输。受光放大器自身的噪声特性影响，信号经过每级光放大后，其信噪比均会有一定程度的劣化，考虑到接收端信噪比的要求，当信噪比劣化到一定程度时，需要加电中继，进行信号再生。

传统的光网络中继单元由掺铒光纤放大器（EDFA)组成，低功率的信号光直接进入 EDFA 进行放大，再向下一级传送。这种结构的缺点在于 EDFA 引入的噪声过大，信噪比的劣化比较快，限制了级联数目的增加，从而限制了无电中继的距离。

由放大器级联理论可知，第一级放大器的噪声特性对整个放大单元的噪声特性影响最大，如果信号先由低噪声的放大器放大，将决定整个放大单元噪声特性优于单纯用 EDFA 做中继。

喇曼（RAMAN）光纤放大器因其具有低噪声特性被认为是实现无电中继长距离传输的基础。随着 RAMAN 光纤放大器的逐渐成熟，光通信系统迈入了新的阶段。RAMAN 光纤放大器是利用光纤中受激喇曼散射（SRS）效应工作的。RAMAN 光纤放大器的主要特点是：可做成连续放大器，在普通通信光纤中连续放大；性能稳定，具有双向性，对反射光不敏感；增益范围可以连续选择，如果泵浦光波长合适，则 RAMAN 光纤放大器可对任何波长

的光进行放大。因为 RAMAN 光纤放大器对信号提供的增益通常为十几个 dB，不能提供足够的增益，也就是说仅靠 RAMAN 光纤放大器自身来完成一个光信号的中继是不现实的，所以综合性能成本，在实际系统中采用喇曼、掺铒光纤混合结构光纤放大器来实现信号的中继。图 1 为当前 RAMAN+EDFA 放大器作为中继单元的一般结构，该中继单元由 RAMAN 光纤放大器 101、可调衰减器（VOA）102 和 EDFA 103 组成，其中 VOA 103 用于调节增益谱均衡。实验证明，这种结构的放大器的噪声特性远远优于相同规格的单纯 EDFA，从而增加了级联数目，大大扩展了无电中继的距离。

在密集波分复用（DWDM）系统中，要求光放大器对各信道的增益保持基本一致，也就是说要增益均衡或增益平坦。众所周知由于掺铒光纤本身的特性，EDFA 的增益谱是不平坦的，需要加入增益平坦滤波器（GFF）进行均衡。图 2 为未加 GFF 的 EDFA 典型增益谱。为了使其增益谱较为平坦，必须添加一个与之匹配的 GFF，则该 GFF 的插损谱如图 3 所示。

当采用 RAMAN + EDFA 放大器结构时，RAMAN 光纤放大器也将引入增益谱的不平坦。针对这种结构目前主要采用两种解决方法：一种是 RAMAN 光纤放大器和 EDFA 分别加 GFF 进行平坦，其优点是模块灵活组合的能力强，但增加了 GFF 个数，引入更多的附加损耗，降低了性能，同时又增加了成本。因此通常选择另一种方法，该方法虽然也是将 RAMAN 光纤放大器和 EDFA 分别进行设计，但将两种放大器的增益谱合起来进行平坦，在这种方法里一般 GFF 放在 EDFA 中。如图 4 所示为根据该方法设计的用于两波长泵浦 RAMAN 光纤放大器+EDFA 放大器结构的 GFF 的插损谱。但这种模块设计中的缺陷是，还是将 RAMAN 光纤放大器的增益谱和 EDFA 的增益谱孤立起来，分别考虑，造成的结果是，RAMAN 光纤放大器和 EDFA 的增益谱叠加起来变得更陡峭。由图 3 和图 4 比较可知，GFF 的深度增加了 2dB 左右。对于 GFF 制造者而言，越深、越陡的曲线，设计的难度就越大，生产和监控都更困难，从而成本就越高，产品特性如误差函数、

附加损耗等就越差；而对于 GFF 使用者而言，GFF 可替代性差，价格高，性能降低。特别地，即使 GFF 性能不变，由于放大器固有的插入损耗的增加，也导致了功率的浪费，以及噪声特性的劣化。

发明内容

有鉴于此，本发明的目的在于提供一种使 RAMAN + EDFA 放大器的增益谱均衡的方法，能够使 RAMAN + EDFA 放大器的增益谱线更加平坦，以减小 GFF 的深度，提高 GFF 的可生产性，从而降低放大器的内部插损、噪声、功率损耗，及其成本。

为达到上述目的，本发明的技术方案是这样实现的：

一种使喇曼掺铒光纤放大器的增益谱均衡的方法，应用于含有至少两个以上不同波长泵浦的喇曼光纤放大器，包括以下步骤：

a. 将掺铒光纤放大器的增益谱线翻转，等比例平移到喇曼光纤放大器增益谱线所在的位置范围，并设定该平移后的增益谱线为目标曲线；

b. 根据目标曲线、精度要求以及成本确定喇曼光纤放大器的泵浦数目以及每个泵浦的波长，其中，精度要求是将输出增益谱的平坦度控制在固定增益范围内；

c. 根据目标曲线、精度要求以及步骤 b 得到的泵浦数目确定每个泵浦的波长和功率值；

d. 调节喇曼光纤放大器中的泵浦数目为步骤 b 所确定的泵浦数目，调节喇曼光纤放大器中每个泵浦的波长和功率为步骤 c 所确定的波长和功率值。

该方法步骤 b 所述的精度要求是将输出增益谱的平坦度控制在固定范围内。

步骤 c 中喇曼光纤放大器每个泵浦的波长和泵浦功率的确定是通过单纯形算法与共轭方向算法相结合的工程优化的方法实现。其中，单纯形算法与共轭方向算法结合进一步包括：

c1. 以每个泵浦的波长和功率值分别作为优化变量，构造一个单纯形，采用单纯形算法对其进行优化;

c2. 对步骤 c1 优化后得到的含有优化变量的顶点采用共轭方向算法进一步优化，直到对优化变量通过仿真算法得到的性能曲线与目标曲线接近到满足精度要求。

步骤 c1 进一步包括：将至少两倍于优化变量的值作为优化变量数目，构造一个单纯形。

步骤 c2 中所述性能曲线与目标曲线接近到满足精度要求是所得性能曲线相对目标曲线的误差平方和小到精度允许的范围。

由于本发明综合地考虑了 RAMAN 光纤放大器和 EDFA 的增益谱，并通过调节 RAMAN 光纤放大器的增益谱使之与 EDFA 互补，GFF 的深度大大减小了。对 GFF 的生产者来说，可生产性好，性能提高，成本下降。对 GFF 的使用者来说，放大器模块的内部插损减小，功率浪费少，噪声性能好，同时放大带宽增加，成本也有所下降。

附图说明

图 1 为 RAMAN+EDFA 结构的光中继单元示意图;

图 2 为 EDFA 的增益谱曲线;

图 3 为用于 EDFA 的典型 GFF 插损谱;

图 4 为一个用于 RAMAN+EDFA 的 GFF 插损谱;

图 5 为 RAMAN 增益因子分布图;

图 6 为单泵浦的 RAMAN 光纤放大器增益谱;

图 7 为两泵浦的 RAMAN 光纤放大器增益谱;

图 8 为本发明方法实施例的流程图;

图 9 为实施例中通过本发明方法优化后的 RAMAN 光纤放大器增益谱;

图 10 为实施例中根据本发明方法优化后增益谱设计的 GFF 与原来的 GFF 的插损谱比较。

具体实施方式

下面结合附图及具体实施例对本发明再作进一步详细说明。

对于 RAMAN 光纤放大器而言，单一波长的泵浦光只能对大约 40nm 的有限波长范围内的信号光进行有效的放大，信号光与泵浦光的频率差为 13THz，相对国际电联（ITU-T）的标准波长而言，即波长相隔 100nm 左右的地方实现最大的增益。图 5 表示了 RAMAN 增益因子的分布情况，纵坐标是增益因子，其与增益量成正比，横坐标是泵浦光与信号光之间的频率差。

对 RAMAN 光纤放大器选择特定波长的泵浦光，将对特定波段的信号光进行放大。图 6 表示了泵浦波长为 1450nm 的单泵浦 RAMAN 光纤放大器的增益谱，从图中可以看出，其最大增益（Max Gain）为 12.82dB，最小增益（Min Gain）3.923dB，其增益平坦度（Flatness）为 8.896dB。

为了实现整个传输带宽内较均衡的增益，必须使用多个波长的泵浦光。比如 C BAND，即 1427~1461nm 带至少两个泵浦，在 C+L BAND，即 1427~1605nm 带至少 3 个泵浦。通过合理选择泵浦波长，调整不同波长的泵浦功率，可以调节不同波长的信号光的增益，这就是增益谱可调的原因，也是 RAMAN 光纤放大器固有的优点。图 7 是双泵浦波长 RAMAN 光纤放大器增益谱的一个典型例子。从图中可以看出，其最大增益为 10.95dB，最小增益 8.982dB，增益谱的平坦度达到了 1.975dB，较之图 6 中的一个泵浦的增益谱曲线已有明显的增加。

单从 RAMAN 光纤放大器角度看，这个增益谱是可以接受的。但是一旦和 EDFA 级联起来，会发现总的增益谱变得更加陡峭，从而所用的 GFF 深度增加，图 4 的 GFF 就是一个例子。这是由于设计 RAMAN 光纤放大器的时候，没有综合考虑整体效果，将 RAMAN 光纤放大器和 EDFA 隔离起来考虑的结果。在设计 RAMAN 光纤放大器时，应该对增益谱进行充分的考虑，使它能够尽量地和 EDFA 进行互补。也就是说，在设计 RAMAN 光纤放大器时，对各个泵浦的波长和功率的选择不能只考虑 RAMAN 光纤放大器

自身的增益特性，而是要将与之串联的EDFA也考虑进去。简单地说，就是在EDFA增益大的波段RAMAN增益小，EDFA增益小的波段RAMAN增益大。

以在C BAND下为例，参见图8所示流程图，对本发明方法的步骤做具体说明。

步骤801，将EDFA的增益谱进行翻转，并按比例向下平移到RAMAN光纤放大器的增益谱线所在范围，得到一条目标增益谱曲线。

步骤802，根据目标曲线的形状、精度要求以及成本确定RAMAN光纤放大器的泵浦数目。考虑到该波长范围内目标曲线有两个峰值，因此至少应选择两个不同波长的泵浦；又考虑到放大后的输出光还要通过GFF继续平坦，不需要很高的精度，只要将RAMAN+EDFA放大器的输出谱平坦度控制在4dB以内就可以了，并考虑到尽量节省成本，因此采用两个不同波长的泵浦就足够了。

步骤803，采用工程优化的办法，确定RAMAN光纤放大器两泵浦的波长和功率值，以使RAMAN光纤放大器的增益谱与目标增益谱尽量接近。

这里喇曼光纤放大器每个泵浦波长和泵浦功率的确定，是采用单纯形（Simplex）算法与共轭方向（Powell）算法相结合的工程优化的方法，首先采用Simplex算法进行初步优化。对于k个优化变量的单纯形法，经典做法是：在k维空间中，以k个优化变量作为其中一个顶点，此顶点的坐标即为各优化变量的初始值，然后再另外随机或者人为构造k个顶点，这样共构造k+1个顶点的单纯形。目的是使单纯形在这k维空间“张开”，比如二维空间中三角形，三维空间中四面体是最基本的单纯形。但是容易发生“低维流形”，比如三角形三个点接近直线，这个单纯形就降为一维的了。因此为了避免上述情况的发生，本发明采用2k个顶点构造单纯形，比如二维空间的矩形，三维空间的多面体。这样大大降低了降维的可能性。在本实施例中假设有n个泵浦，由于每个泵浦有波长和功率两个变量，则总的优化变量就有2n个，

由上可知，对于 2n 个优化变量，本发明的单纯形顶点数取为 4n 而不是 2n+1，这样既不会增加计算量，同时也保证了足够的顶点数。然后用 Simplex 算法进行优化，得到一个较为合适的优化点。这是由于 Simplex 算法具有全局性好、速度快的特点，但它的结果较为粗糙，不够精确。于是再采用 Powell 算法对 Simplex 算法中得到的优化点进行进一步优化。直到这 2n 个优化变量通过仿真算法得到的性能曲线与目标曲线接近到满足精度要求，即误差平方和小到精度要求允许的范围为止，

步骤 804，调节喇曼光纤放大器中的泵浦数目为步骤 802 所确定的泵浦数目，调节喇曼光纤放大器中每个泵浦的波长和功率为步骤 803 所确定的波长和功率值。

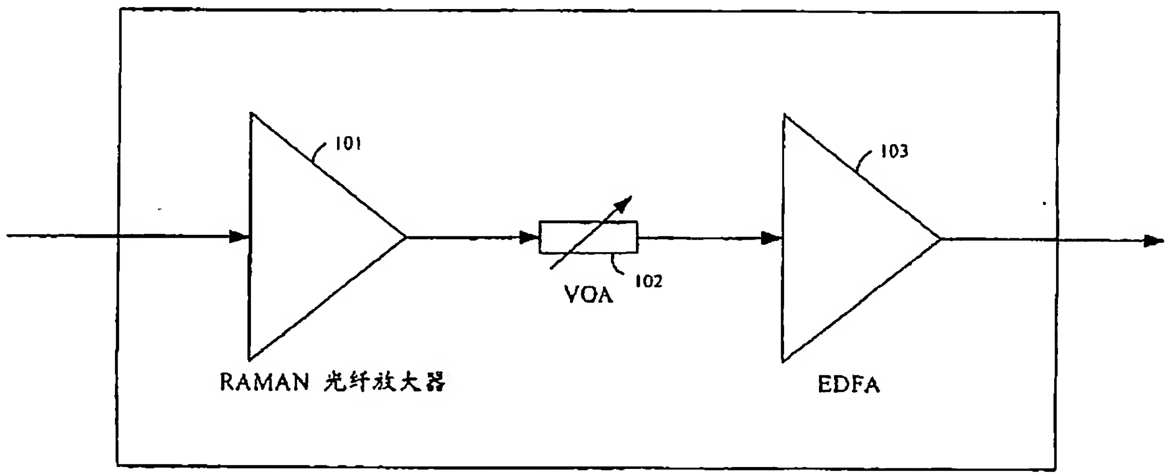
如图 9 所示为本实施例中优化后的 RAMAN 光纤放大器增益谱曲线与翻转的 EDFA 增益谱即目标增益谱曲线的比较。图 9 可以看出，优化后的 RAMAN 光纤放大器增益谱曲线 901 与目标曲线 902 已十分接近。RAMAN 增益谱曲线 901 在保证增益绝对量的同时，应尽量与目标曲线 902 达成一致。由图中看出，RAMAN 光纤放大器的最大增益 11.00dB，最小增益 8.829dB，有效增益约为 10dB，平坦度约为 2.17dB，叠加 EDFA 增益谱以后，平坦度达到 3.772dB。

之后，再根据优化后的 RAMAN 光纤放大器增益谱与 EDFA 增益谱的叠加曲线，设计所需 GFF 的插损曲线。

图 10 显示了新老 GFF 的插损谱比较。新 GFF 插损曲线 1001 的深度为 3.8dB，老 GFF 插损曲线 1002，即图 4 中的根据未优化的 RAMAN 光纤放大器与 EDFA 的增益谱相叠加而设计的 GFF 插损曲线，它的深度为 7.2dB。不难看出，新设计方案产生的 GFF 大大优于原先的 GFF。

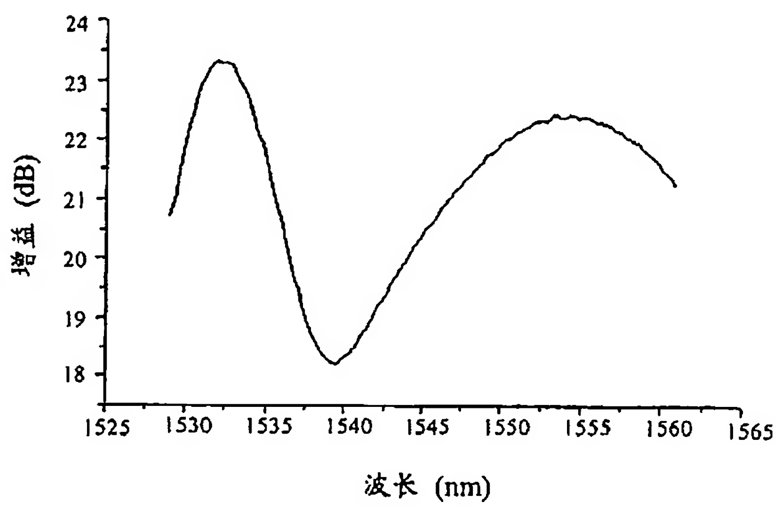
当然，如果采用更多的泵浦其增益谱曲线与目标曲线匹配效果会更好，这样就可以根据不同的需要来选择 RAMAN 光纤放大器泵浦的数目和泵浦波长，更好的实现 RAMAN+EDFA 结构的放大器的增益均衡。

以上所述，仅为本发明的较佳的实施例而已，并非用于限定本发明的保护范围。



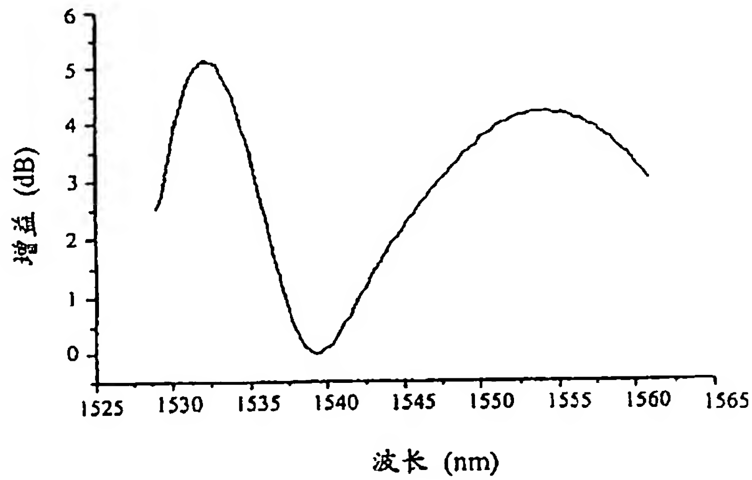
101
103
VOA
102
RAMAN 光纤放大器
EDFA

图 1



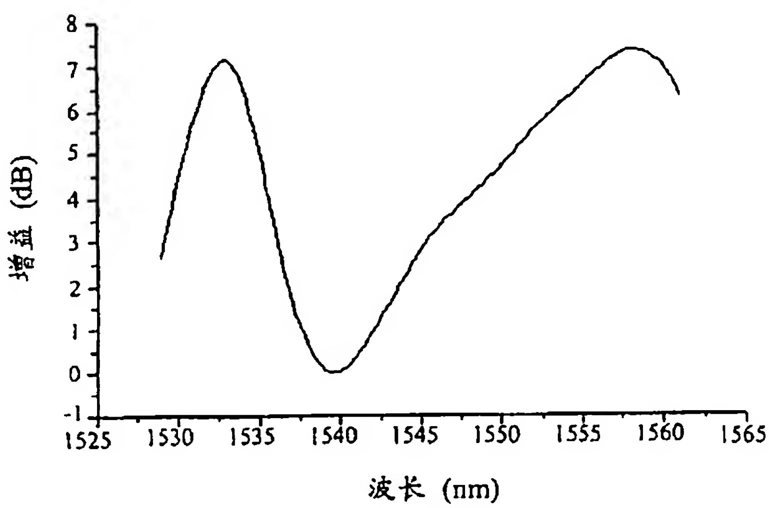
24
23
22
21
20
19
18
增益 (dB)
1525
1530
1535
1540
1545
1550
1555
1560
1565
波长 (nm)

图 2



增益 (dB)
6
5
4
3
2
1
0
1525
1530
1535
1540
1545
1550
1555
1560
1565
波长 (nm)

图 3



增益 (dB)
8
7
6
5
4
3
2
1
0
-1
1525
1530
1535
1540
1545
1550
1555
1560
1565
波长 (nm)

图 4

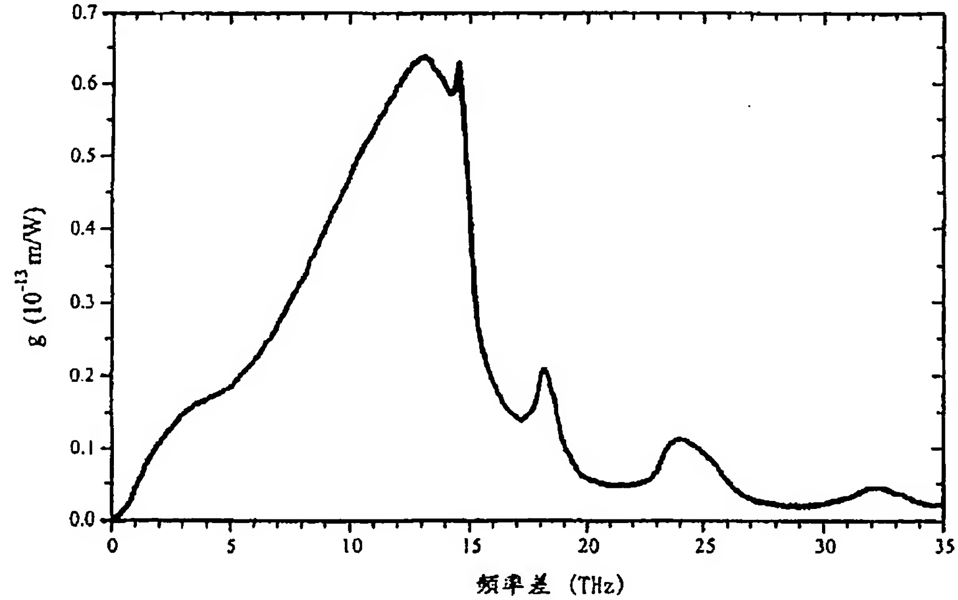

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
g (10^{-13} m/W)
0
5
10
15
20
25
30
35
频率差 (THz)

图 5

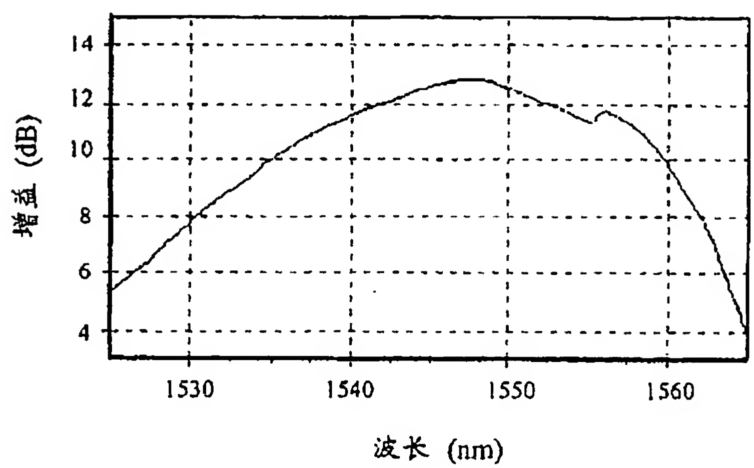

14
12
10
8
6
4
增益 (dB)
1530
1540
1550
1560
波长 (nm)

图 6

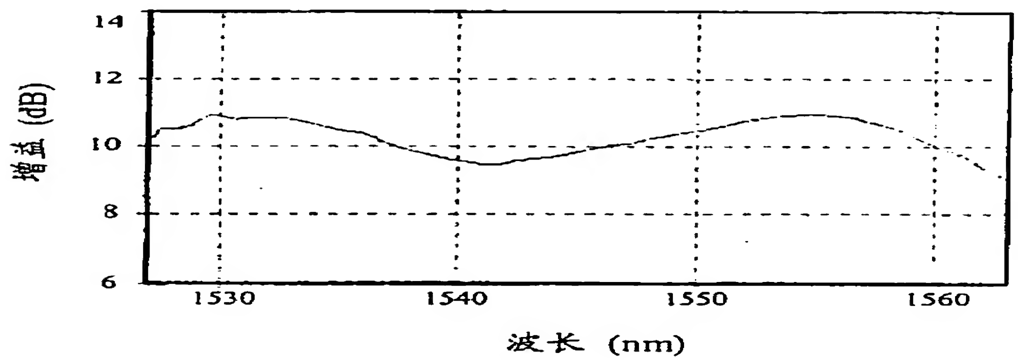

14
12
10
8
6
增益 (dB)
1530
1540
1550
1560
波长 (nm)

图 7

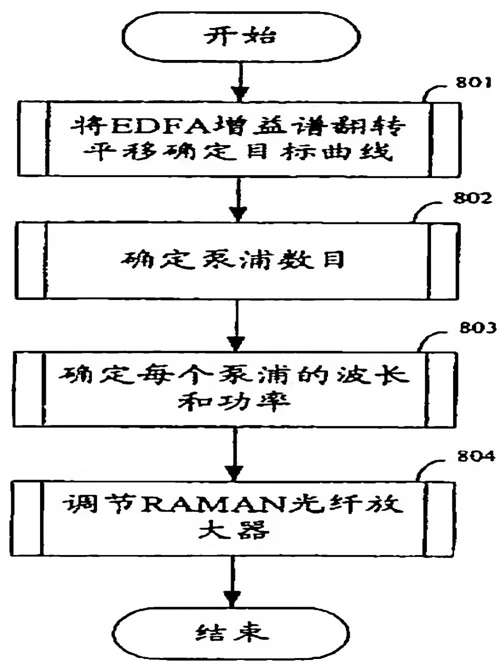

开始
将EDFA增益谱翻转平移确定目标曲线
801
确定泵浦数目
802
确定每个泵浦的波长和功率
803
调节RAMAN光纤放大器
804
结束

图 8

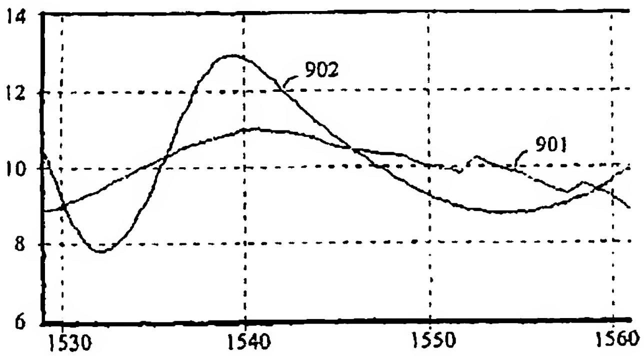

14
12
10
8
6
902
901
1530
1540
1550
1560

图 9

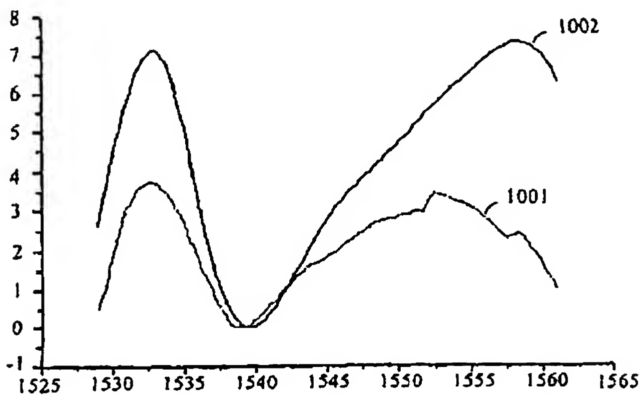

8
7
6
5
4
3
2
1
0
-1
1002
1001
1525
1530
1535
1540
1545
1550
1555
1560
1565

图 10

Method for uniformizing gain spectrum of Raman erbium dosed oplical fiber amplifier

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Inventor: LIN DONG (CN)
Applicant: HUAWEI TECHNOLOGICAL CO LTD (CN)
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- European:
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Priority number(s): CN20021031442 20021014

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CN1315274C (C)

Abstract of **CN1490659**

The method includes the following steps: a) turning gain spectral line of erbium-doped fibre amplifier over and shifting it to position scope of Raman fibre amplifier gain spectral line in equal ratio translation, setting the traslated gain spectral line as target curve; b) according to the target curve, accuracy reguirement and cost to set pumping number for the Raman fibre amplifier; c) according to the target curve, accuracy requirement and the pumping number obtained from setp b) to set wavelength and power value for each pumping; d) according to results of step b) and c) to regulate the Raman fibre amplifier.

Method for Equalizing Gain Spectrum of Raman Erbium-Doped Fiber Amplifier

Publication No.: CN1490659A

Technical Field

This invention relates to a Raman erbium-doped fiber amplifier technique, and in particular, to a method for equalizing the gain spectrum of a Raman erbium-doped fiber amplifier.

Background Art

All existing optical network systems use an optical amplifier as the relay unit for amplifying the signal attenuated after optical fiber transmission so as to make the signal transfer to the next stage. Affected by the noise characteristic of the optical amplifier itself, the signal-to-noise ratio of the signal undergone every stage of optical amplification will have a certain degree of degradation. Considering the requirement for signal-to-noise ratio at the receiving end, power-on relay is required for signal regeneration when the signal-to-noise ratio degrades to a certain degree.

Conventional optical network relay unit consists of an erbium-doped fiber amplifier (EDFA), and lower power signal light enters the EDFA directly to be amplified and transferred to the next stage. The shortcoming of this structure is that the noise caused by EDFA is too loud, and the signal-to-noise ratio degrades pretty fast, thus limiting the increase of the cascade number, thereby limiting the distance of electroless relay.

It can be learned from the amplifier cascade theory that the noise characteristic of the first stage amplifier has the greatest influence on the

noise characteristic of the entire amplifying unit. If the signal is amplified first by a low noise amplifier, then the noise characteristic of the entire amplifying unit will be better than purely using EDFA as the relay.

Raman fiber amplifier, thanks to its low noise characteristic, is regarded as the basis for achieving electroless relay long distance transmission. As the Raman fiber amplifier gradually matures, optical communication system enters a new phase. Raman fiber amplifier operates by the stimulated Raman scattering (SRS) effect in optical fiber. The main characteristics of Raman fiber amplifier are: capable of being made a continuous amplifier for continuous amplification in common communication fiber; stable in performance, bidirectional, insensitive to reflected light; gain range being continuously selectable, and if the pump light wavelength is suitable, Raman fiber amplifier can amplify light of any wavelength. As the gain provided to signals by the Raman fiber amplifier is usually about a dozen of dBs, no enough gain can be provided, or in other words, it is not realistic to rely only on the Raman fiber amplifier alone to complete the relay of an optical signal, so synthesizing the performance cost, a fiber amplifier of Raman and erbium-doped fiber hybrid structure is used in actual practice to implement the relay of signals. Fig. 1 is a general structure of the current Raman+EDFA amplifier as a relay unit, which is composed of Raman fiber amplifier 101, adjustable attenuator (VOA) 102 and EDFA 103, wherein the VOA 103 is used for adjusting the gain spectrum equilibrium. Experimental verification shows that the noise characteristic an amplifier of such structure is far better than pure EDFA of the same specification, thereby increasing the cascade number and greatly expanding the distance of electroless relay.

In a dense wavelength division multiplexing (DWDM) system, the optical amplifier is required to keep the gains of various channels basically

consistent, or in other words, to be gain equal or gain flat. It is known to all that, due to the characteristic of the erbium-doped fiber per se, the gain spectrum of EDFA can not be flat, so a gain flat filter (GFF) should be included to perform equalization. Fig. 2 is a typical gain spectrum of EDFA without GFF. To make its gain spectrum relatively flat, a matching GFF shall be added thereto, then the inserting loss spectrum of said GFF is as shown in Fig. 3.

When the Raman+EDFA amplifier structure is adopted, the Raman fiber amplifier will also introduce the unevenness of the gain spectrum. Currently there are main two solutions for this structure: one is that the Raman fiber amplifier and EDFA respectively include GFF to flat; its advantage is the module's strong ability to flexibly combine, but the number of GFFs is increased, thereby incurring more additional loss and reducing the performance, as well as increasing cost. Therefore, the other solution is usually adopted. Although this other solution also respectively designs the Raman fiber amplifier and EDFA, the gain spectrums of the two amplifiers are added together to flat, and in this solution it is usual to put GFF in EDFA. Fig. 4 shows the inserting loss spectrum of the GFF designed according to said solution for the two wavelength pump Raman fiber amplifier plus EDFA amplifier structure. However, this module design has the defect of isolating the gain spectrum of the Raman fiber amplifier from the gain spectrum of EDFA to be considered separately, thus resulting in the gain spectrums of the Raman fiber amplifier and EDFA being superposed to become steeper. It can be seen from the comparison between Fig. 3 and Fig. 4 that the depth of GFF is increased by approximately 2 dBs. To the GFF manufacturer, the deeper and steeper the curve is, the harder the design will be, and so are the production and supervision, and the cost will be higher, while the product characteristics such as error function and additional loss will be worse; for the GFF user, the GFF is not easy to replace but is high in price and low in performance.

In particular, even if the performance of GFF does not change, the increase of the intrinsic inserting loss of the amplifier also incurs waste of power and degradation of noise characteristic.

Contents of the Invention

In view of the above, the purpose of this invention is to provide a method for equalizing the gain spectrum of the Raman+EDFA amplifier, being able to make the gain spectral line of the Raman+EDFA amplifier more flat, decrease the depth of GFF and improve the producibility of GFF, thereby reducing the internal inserting loss, noise, power consumption of the amplifier and the cost thereof.

To achieve the above purpose, the technical solution of this invention is carried out in the following way:

A method for equalizing the gain spectrum of a Raman erbium-doped fiber amplifier, being applicable to the Raman fiber amplifier having at least two or more pumps of different wavelengths, and including the following steps:

a. invert the gain spectral line of the erbium-doped fiber amplifier, translate at equal ratio to the range of position where the gain spectral line of the Raman fiber amplifier locates, and set the translated gain spectral line as a target curve;

b. determine the number of pumps of the Raman fiber amplifier and the wavelength of each pump on the basis of the target curve, requirement for precision and cost, wherein the requirement for precision is to control the flatness of the output gain spectrum within a fixed range of gain;

c. determine the wavelength and power value of each pump on the basis of the target curve, the requirement for precision and the number of pumps obtained in step b;

d. adjust the number of pumps in the Raman fiber amplifier to be the number of pumps determined in step b, and adjust the wavelength and power of each pump in the Raman fiber amplifier to be the wavelength and power value determined in step c.

The requirement for precision stated in step b of this method is to control the flatness of the output gain spectrum within a fixed range of gain.

The determination of each pump wavelength and pump power of the Raman fiber amplifier in step c is realized by an engineering optimization method that combines the simplex algorithm with the Powell algorithm, wherein the simplex algorithm and the Powell algorithm are combined to further include:

c1. using the wavelength and power value of each pump respectively as the optimizing variables to construct a simplex, and using the simplex algorithm to optimize it;

c2. using the Powell algorithm to further optimize the vertex containing the optimizing variables obtained after optimizing step c1, until the performance curve obtained by the simulation algorithm on the optimizing variables approaches the target curve by the requirement for precision.

Step c1 further comprises: using the value that at least doubles the optimizing variables as the number of optimizing variables to construct a simplex.

The performance curve approaching the target curve by the requirement for precision as stated in step c2 is a square error of the performance curve over the target curve and is small enough to fall within an allowable range of precision.

In this invention, the gain spectrums of the Raman fiber amplifier and EDFA are taken into consideration comprehensively, and the gain spectrum of the Raman fiber amplifier is adjusted to be complementary with EDFA, so the depth of GFF is considerably reduced. To the GFF manufacturer, the producibility is fine, the performance is improved, and the cost is low; to the GFF user, the internal inserting loss of the amplifier module is decreased, the waste of power is reduced, the noise characteristic is good, and at the same time, the bandwidth is widened and cost is lowered to a certain extent.

Description of Figures

Fig. 1 is a schematic diagram of the optical relay unit of Raman+EDFA structure;
Fig. 2 is the gain spectrum curve of EDFA;
Fig. 3 is a typical GFF inserting loss spectrum for EDFA;
Fig. 4 is a GFF inserting loss spectrum for Raman+EDFA;
Fig. 5 is a Raman gain factor distribution chart;
Fig. 6 is the Raman fiber amplifier gain spectrum of single pump;
Fig. 7 is the Raman fiber amplifier gain spectrum of double pumps;
Fig. 8 is a flow chart of the embodiment of the method of the present invention;
Fig. 9 is the Raman fiber amplifier gain spectrum optimized by the method of the present invention in the embodiment;
Fig. 10 is a comparison of the GFF designed according to the gain

spectrum optimized by the method of the present invention with the inserting loss spectrum of the original GFF in the embodiment.

Mode of Carrying out the Invention

Following are further explanation of the present invention with reference to the figures and the specific embodiments.

For a Raman fiber amplifier, pump light of single wavelength can only effectively amplify signal light within limited range of wavelength about 40 nm. The frequency difference between signal light and pump light is 13 THz, and relative to the standard wavelength of International Telecommunications Union (ITU-T), that is to say that maximum gain is achieved at the place where wavelength interval is about 100 nm. Fig. 5 is a Raman gain factor distribution chart, wherein the ordinate is a gain factor proportional to the amount of gain, and the abscissa is a frequency difference between pump light and signal light.

Pump light of particular wavelength is selected for the Raman fiber amplifier to amplify signal light of particular wave band. Fig. 6 is the Raman fiber amplifier gain spectrum of single pump whose pump wavelength is 1450 nm. It can be seen from the figure that its max gain is 12.82 dB, min gain is 3.923 dB, and gain flatness is 8.896 dB.

To achieve fairly equalized gain within the entire transmission bandwidth, pump light of multiple wavelengths shall be used. For example, C band, i.e. at least two pumps at 1427-1461 nm band, and at least three pumps at 1427-1605 nm band. By reasonably selecting the pump wavelength to adjust pump power of different wavelengths, gain of signal light of different wavelengths can be adjusted, and this is the reason why the gain spectrum is adjustable, and the intrinsic advantage of Raman fiber

amplifier. Fig. 7 is a typical instance of a double pump wavelength Raman fiber amplifier gain spectrum. It can be seen from the figure that its max gain is 10.95 dB, min gain is 8.982 dB, and the flatness of gain spectrum reaches 1.975 dB, being obviously increased compared with the gain spectrum curve of signal pump in Fig. 6.

Viewing from the angle of the Raman fiber amplifier alone, this gain spectrum is acceptable. However, once it is cascaded with EDFA, the gain spectrum is found to become steeper, so the GFF in use gains more depth. The GFF in Fig. 4 is a good example. This is because that the overall effect is not taken into comprehensive consideration when designing Raman fiber amplifier, resulting from separating the Raman fiber amplifier from EDFA during consideration. When designing Raman fiber amplifier, full consideration shall be given to the gain spectrum to make it complementary with EDFA as far as possible. In other words, when designing the Raman fiber amplifier, the selection of the wavelength and power for each pump shall not consider only the gain characteristic of the Raman fiber amplifier itself, but should also take the EDFA connected in series with it into consideration. Simply put, Raman gain is small at the band where EDFA gain is large; and Raman gain is large at the band where EDFA gain is small.

The steps of the method of the present invention are explained in detail as follows with C band as an example with reference to the flow chart shown in Fig. 8.

Step 801: invert the gain spectrum of EDFA and translate proportionally to the range where the gain spectral line of the Raman fiber amplifier locates, obtain a target gain spectral line.

Step 802: determine the number of pumps of the Raman fiber amplifier

on the basis of the shape of target curve, the requirement for precision and the cost. Considering that the target curve within said range of wavelength has two peaks, so at least two pumps of different wavelengths should be selected; and considering that the amplified output light still needs to pass through GFF to continue to flat, the precision does not have to be very high, so the output spectrum flatness of the Raman+EDFA amplifier being controlled within 4 dB will be okay. Besides, to save cost as much as possible, two pumps of different wavelengths are enough.

Step 803: use the engineering optimization method to determine the wavelengths and power values of the two pumps of the Raman fiber amplifier, so as to make the gain spectrum of the Raman fiber amplifier approach the target gain spectrum as close as possible.

Here the determination of each pump wavelength and pump power of the Raman fiber amplifier is realized by the engineering optimization method that combines the simplex algorithm with Powell algorithm. First, the simplex algorithm is adopted to perform initial optimization. For the simplex algorithm having k optimizing variables, the classical practice is: in a k-directional space, take k optimizing variables as one vertex therein, and the coordinate of this vertex is just the initial value of the respective optimizing variables, then construct k vertexes randomly or artificially in addition, thus making a simplex of k+1 vertexes altogether. The purpose is to make this simplex "open" in the k-directional space, e.g. the triangle in a two-dimensional space and the tetrahedron in a three-dimensional space are the most basic simplexes. However, "low-dimensional manifold" is easy to occur, e.g. when the three points of a triangle are close to a straight line, the simplex is then reduced to be one-dimensional. To avoid the above situation, the present invention adopts 2k vertexes to construct the simplex, e.g. rectangle of two-dimensional space and polyhedron of three-dimensional space, thus significantly diminishing the

possibility of dimension reduction. In this embodiment, it is supposed that there are n pumps, and as each pump has such two variables as wavelength and power, the total optimizing variables are 2n in number. It can be seen from above that, regarding the 2n optimizing variables, the number of simplex vertex of the present invention is 4n instead of 2n+1. In this way, the calculation amount is not increased, and at the same time, there will be enough vertexes. Thereafter, the simplex algorithm is adopted to perform optimization to obtain a fairly proper optimizing point. This is because that the simplex algorithm has the feature of comprehensive and fast, but its result is a comparatively rough, being not precise enough. Therefore, the Powell algorithm is adopted to further optimize the optimizing point obtained in the simplex algorithm, until the performance curve obtained by the simulation algorithm on the 2n optimizing variables approaches the target curve by the requirement for precision, namely until the square error and being small enough to fall within an allowable range of precision.

Step 804: adjust the number of pumps in the Raman filter amplifier to be the number of pumps determined in step 802, adjust the wavelength and power of each pump in the Raman filter amplifier to be the wavelength and power value determined in step 803.

Fig. 9 is a comparison of the Raman fiber amplifier gain spectral line optimized in the embodiment with the inverted EDFA gain spectral line, i.e. target gain spectral line. It can be seen from Fig. 9 that the optimized Raman fiber amplifier gain spectral line 901 is very close to the target curve 902. Raman gain spectral line 901, when ensuring the absolute magnitude of the gain, should be consistent with the target curve 902 as far as possible. It can be seen from the figure that the max gain of the Raman fiber amplifier is 11.00 dB, min gain is 8.829 dB, effective gain is about 10 dB, flatness is about 2.17 dB, and after superposing the EDFA

gain spectrum, the flatness reaches 3.772 dB.

Thereafter, the desired GFF inserting loss curve is designed on the basis of the superposed curve of the optimized Raman fiber amplifier gain spectrum and the EDFA gain spectrum.

Fig. 10 shows the inserting loss comparison of the old and new GFFs. The depth of the new GFF inserting loss curve 1001 is 3.8 dB, the old GFF inserting loss curve is 1002, namely the GFF inserting loss curve designed by superposing the EDFA gain spectrum with the Raman fiber amplifier not optimized in Fig. 4, whose depth is 7.2 dB. It is not difficult to see that the GFF generated by the new design scheme is far better than the original GFF.

Certainly, if more pumps are adopted, the matching effect of the gain spectrum curve and target curve will be better, and thus the pump number and pump wavelength of the Raman fiber amplifier can be selected according to different needs, thereby better achieving gain equilibrium of amplifiers of Raman+EDFA structure.

It should be noted that the above are preferable embodiments of the present invention only, being not used for limiting the scope of protection of the present invention.

Abstract

This invention discloses a method for equalizing the gain spectrum of a Raman erbium-doped fiber amplifier, being applicable to the Raman fiber amplifier having at least two or more pumps of different wavelengths, and including the following steps: a. invert the gain spectral line of the erbium-doped fiber amplifier, translate at equal ratio to the range of position where the gain spectral line of the Raman fiber amplifier locates, and set the translated gain spectral line as a target curve; b. determine the number of pumps of the Raman fiber amplifier on the basis of the target curve, requirement for precision and cost; c. determine the wavelength and power value of each pump on the basis of the target curve, the requirement for precision and the number of pumps obtained in step b; d. adjust the Raman fiber amplifier on the basis of the results of step b and step c. The method of this invention can make the gain spectral line of the Raman erbium-doped fiber amplifier more flat in order to decrease the depth of GFF and improve the producibility of GFF, thereby reducing the internal inserting loss, noise, power consumption of the amplifier and the cost thereof.

Claims

1. A method for equalizing the gain spectrum of a Raman erbium-doped fiber amplifier, being applicable to the Raman fiber amplifier having at least two or more pumps of different wavelengths, characterized by including the following steps:

   a. invert the gain spectral line of the erbium-doped fiber amplifier, translate at equal ratio to the range of position where the gain spectral line of the Raman fiber amplifier locates, and set the translated gain spectral line as a target curve;

   b. determine the number of pumps of the Raman fiber amplifier on the basis of the target curve, requirement for precision and cost;

   c. determine the wavelength and power value of each pump on the basis of the target curve, the requirement for precision and the number of pumps obtained in step b;

   d. adjust the number of pumps in the Raman fiber amplifier to be the number of pumps determined in step b, and adjust the wavelength and power of each pump in the Raman fiber amplifier to be the wavelength and power value determined in step c.

2. The method according to claim 1, characterized in that The determination of each pump wavelength and pump power of the Raman fiber amplifier in step c is realized by an engineering optimization method that combines a simplex algorithm with a Powell algorithm.

3. The method according to claim 1, characterized in that the requirement for precision in step b is to control the flatness of the output gain spectrum within a fixed range.

4. The method according to claim 2, characterized in that the simplex algorithm and the Powell algorithm further comprise:

   c1. using the wavelength and power value of each pump respectively as the optimizing variables to construct a simplex, and using the simplex algorithm to optimize it;

   c2. using the Powell algorithm to further optimize the vertex that contains the optimizing variables obtained after optimizing step c1, until the performance curve obtained by the simulation algorithm on the optimizing variables approaches the target curve by the requirement for precision.

5. The method according to claim 4, characterized in that the step c1 further comprises: using the value that at least doubles the optimizing variables as the number of optimizing variables to construct a simplex.

6. The method according to claim 4, characterized in that the performance curve approaching the target curve by the requirement for precision as stated in step c2 is a square error of the performance curve over the target curve and is small enough to fall within an allowable range of precision.

Fig. 1

Raman fiber amplifier

Fig. 2

Gain (dB)

Wavelength (nm)

Fig. 3

Gain (dB)

Wavelength (nm)

Fig. 4

Gain (dB)

Wavelength (nm)

Fig. 5

Frequency difference

Fig. 6

Gain (dB)

Wavelength (nm)

Fig. 7

Gain (dB)

Wavelength (nm)

Fig. 8

Start

801 Invert EDFA gain spectrum and translate the determined target curve

802 Determine the number of pumps

803 Determine the wavelength and power of each pump

804 Adjust Raman fiber amplifier

End